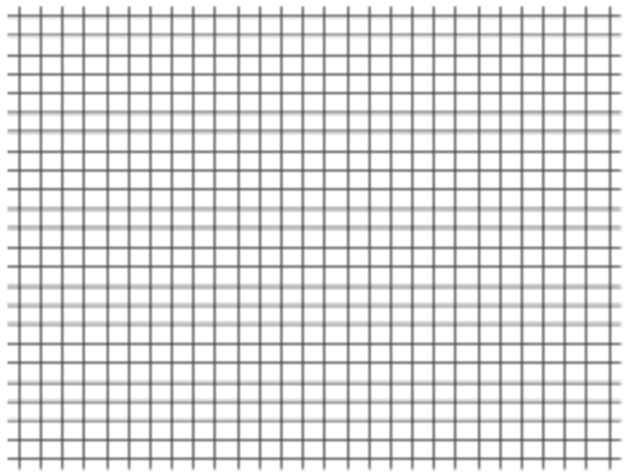
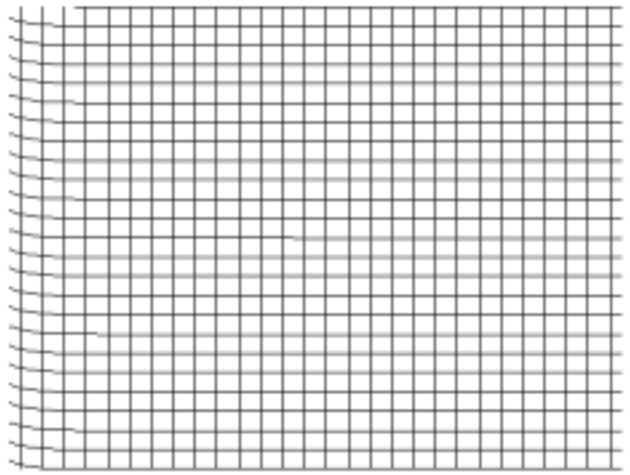
# Generative Music with Haskell

MuniHac 2024

# Physics

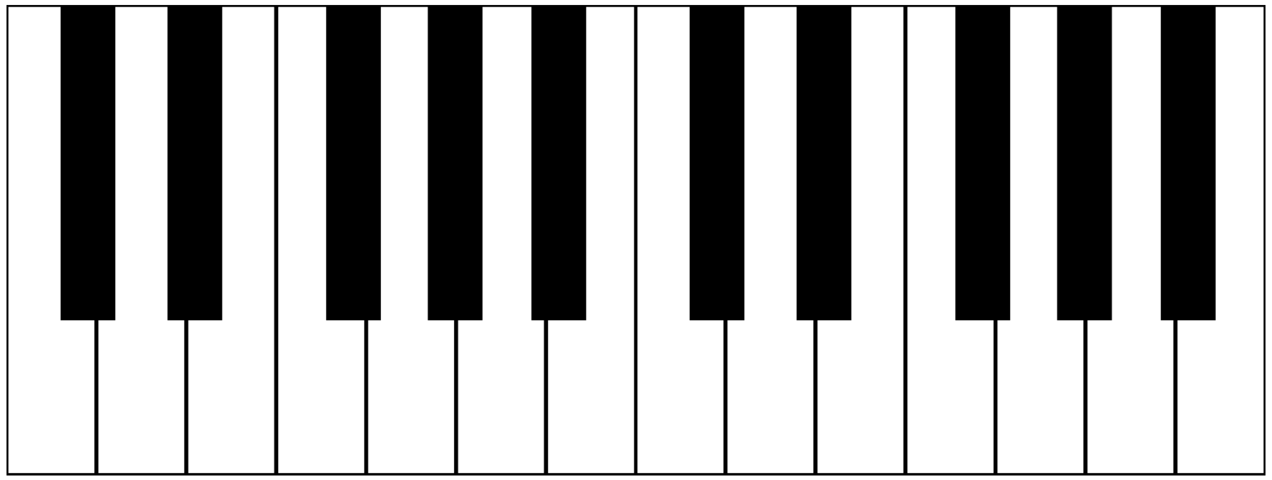
# What is sound?

- A vibration that propagates as a compressive/expansive wave through a transmission medium
- A vibration that propagates as a pressure wave through air

## What characterizes sound?

- Loudness
- Pitch
  - Does all sound have pitch?
  - Are all pitches audible by humans?
    - 20 Hz to 20 kHz
  - Chromatic scale

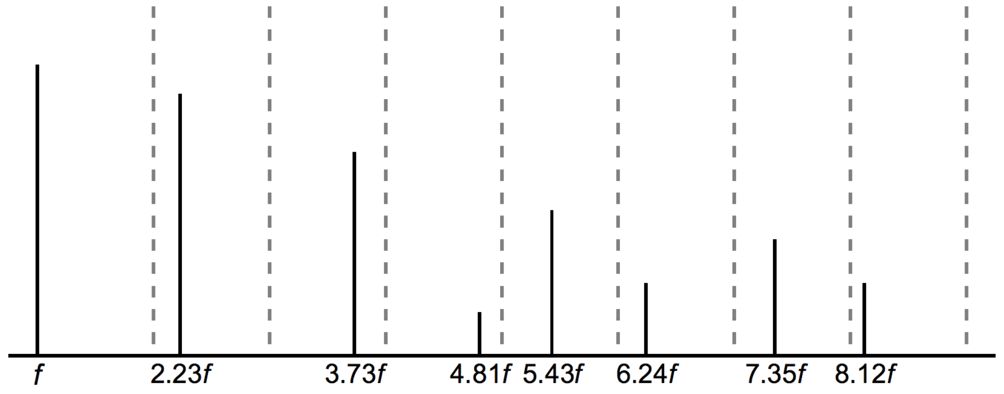


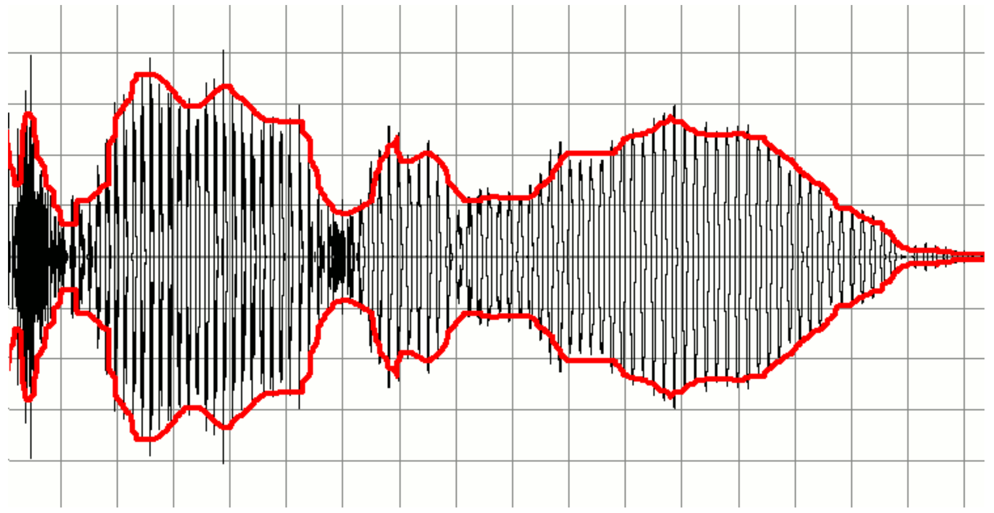
## What characterizes sound?

- Is that it?
- Why does e.g. a flute sound different than a piano, when playing the same note at a similar loudness level?

# What characterizes sound?

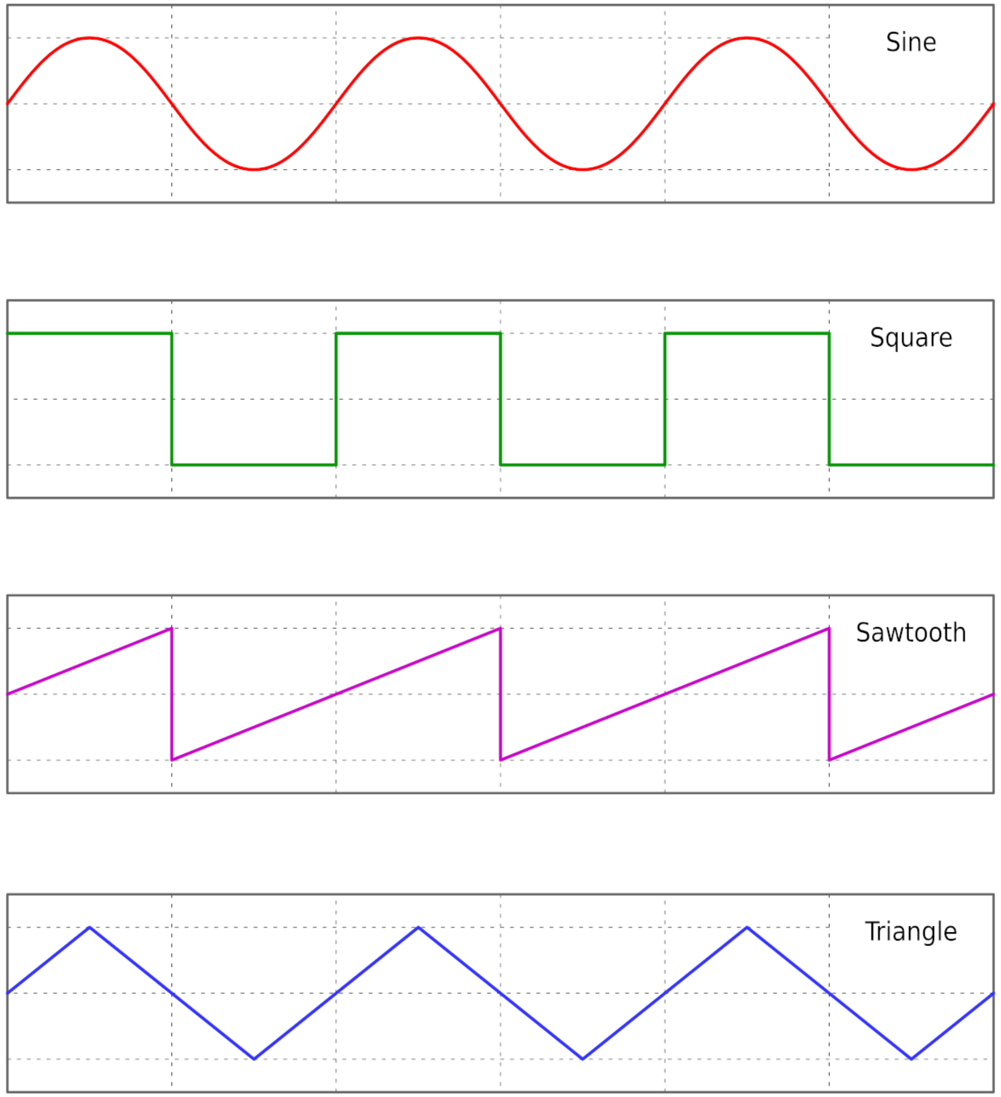
- Timbre /Color
  - Partials
  - Envelopes





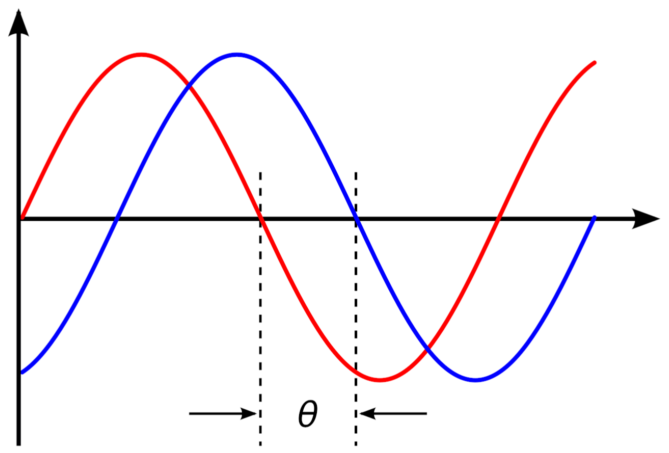
## Simple waveforms

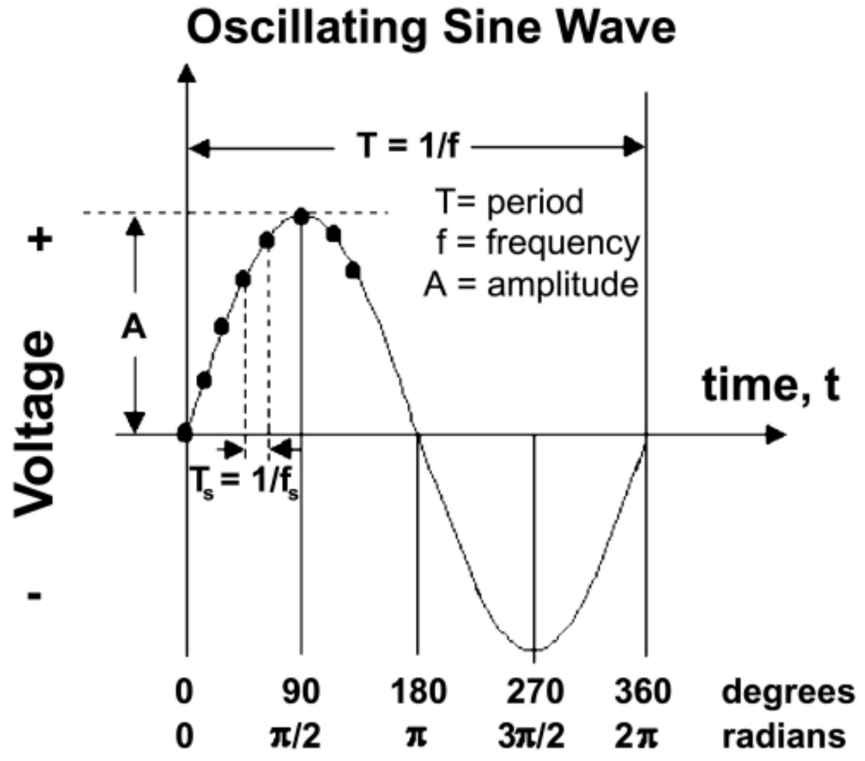
- Sine wave
- Square wave
  - Pulse width / duty cycle
- Sawtooth wave
- Triangle wave



# Simple waveforms

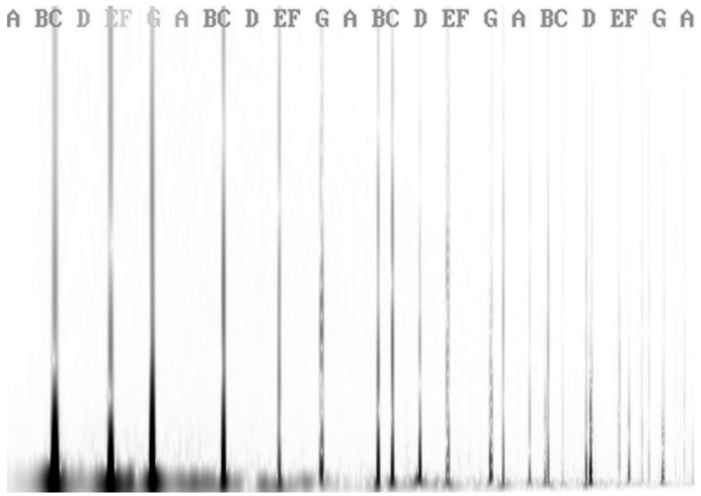
- Properties
  - Amplitude
  - Frequency
  - Phase

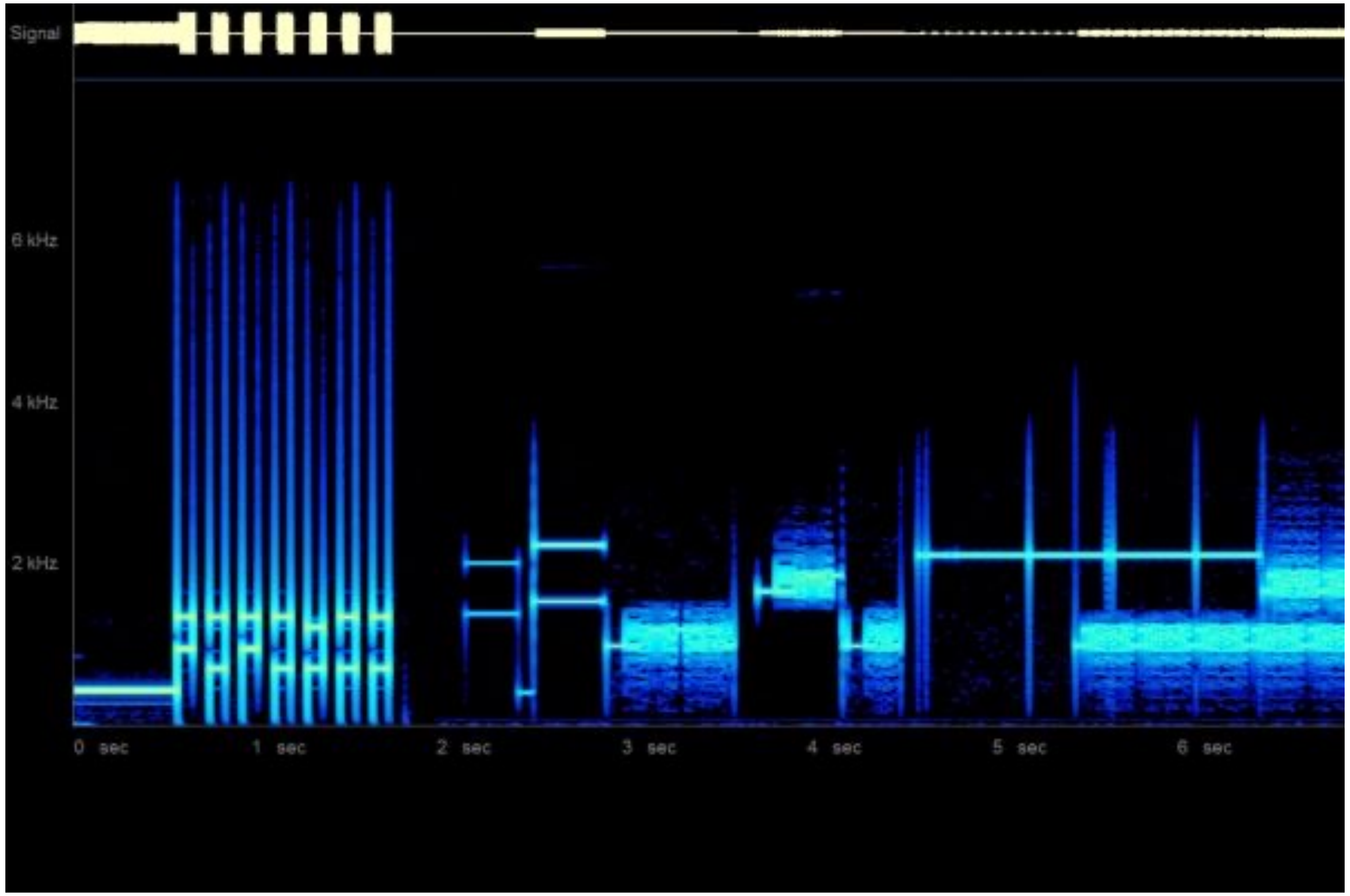




# Time vs Frequency domains

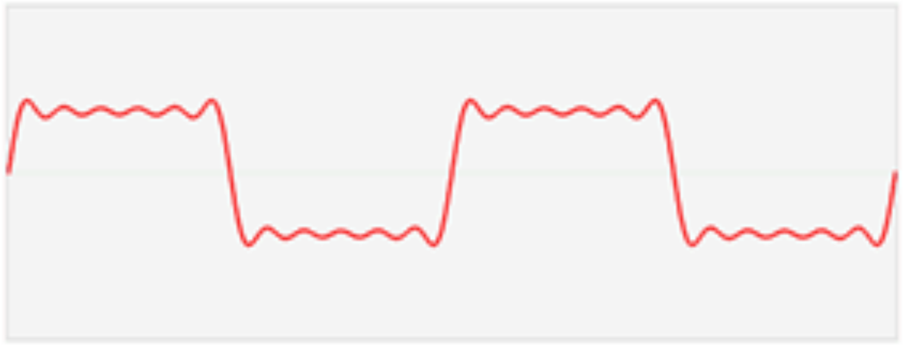
- Amplitud vs Time
- Amplitude vs Frequency
- Spectrogram





## Time vs Frequency domains

- Fourier transform
    - Any function can be represented as a combination of a potentially infinite number of trigonometric functions

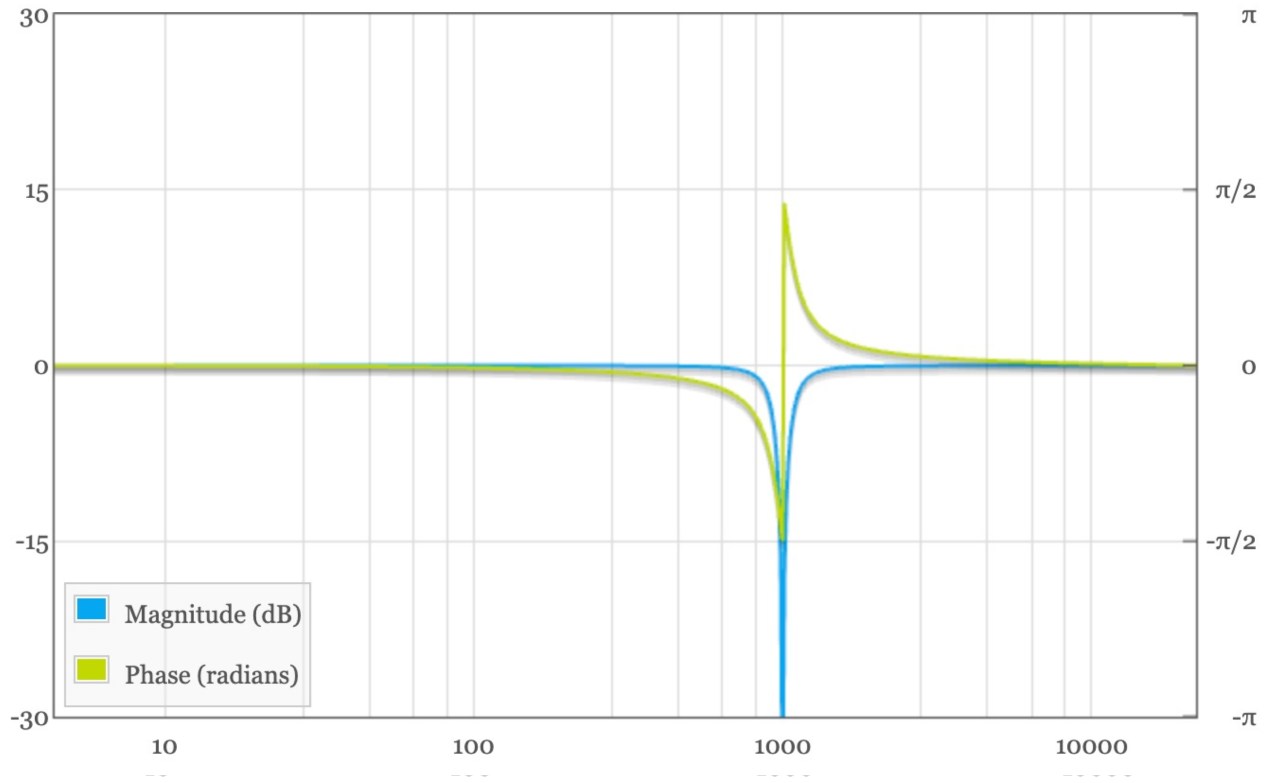


# Time vs Frequency domains

- Partials / harmonics
  - Square wave: Odd harmonics only, $A = 1/n$
  - Sawtooth wave: Odd and even harmonics, $A = (-1)^n/n$
- **Additive synthesis**

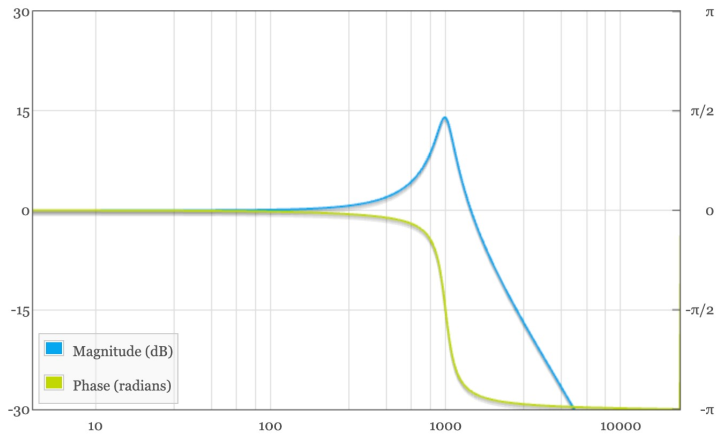
## Filtering

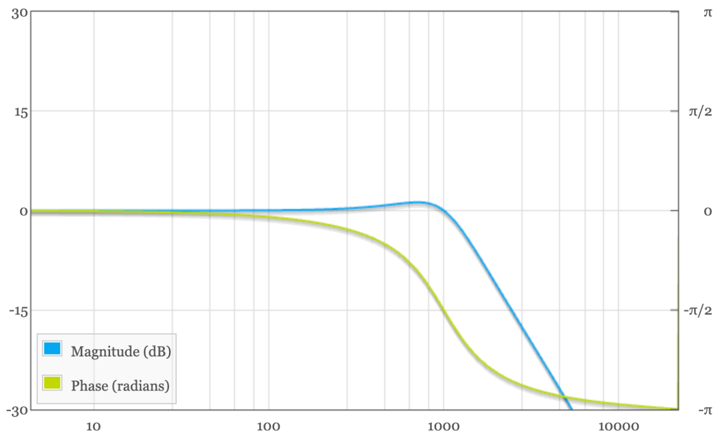
- Operate on the frequency domain, either attenuating or amplifying certain frequencies
- Types of filters
  - Low-pass
  - High-pass
  - Band-pass
  - Notch / Band-stop

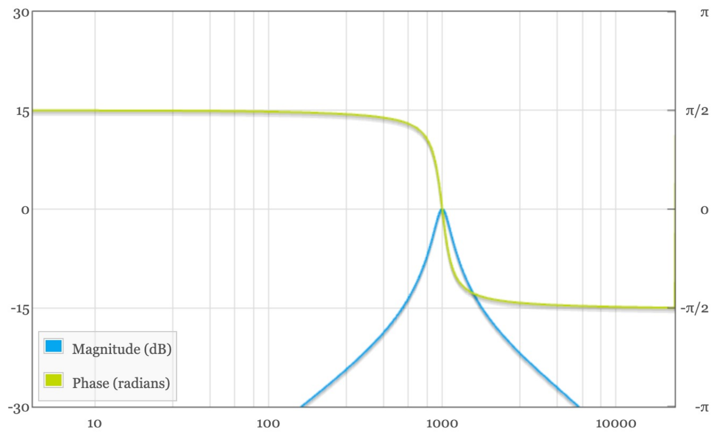


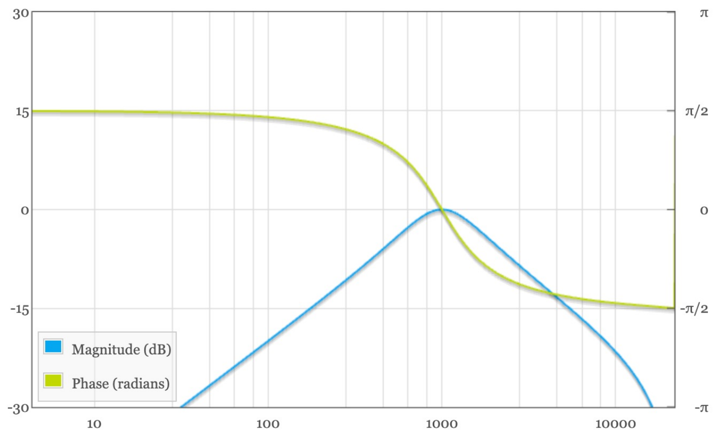
# Filtering

- Characteristics of filters
  - Cutoff frequency
  - Q
  - Bandwidth
  - Gain/Attenuation
- **Subtractive synthesis**



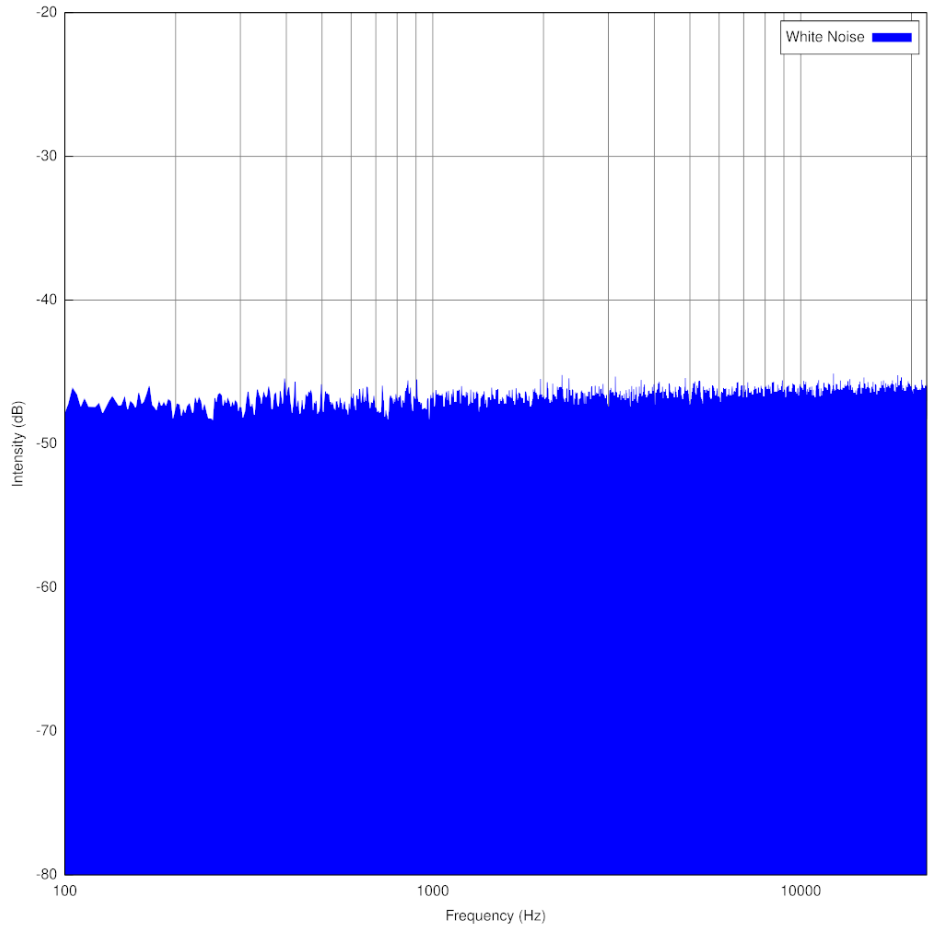






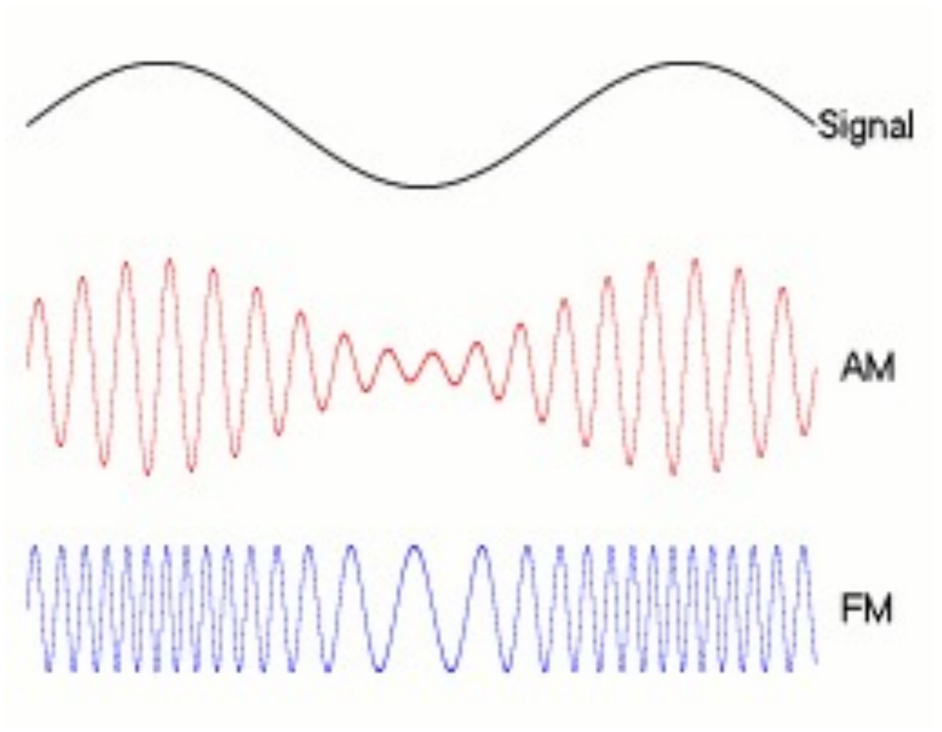
# Noise

- White noise
  - Uniformly distributed random values
  - Contains all frequencies with equal amplitudes
  - Used as a source for subtractive synthesys
  - Used as a sorce of randomness
    - Sample-and-hold



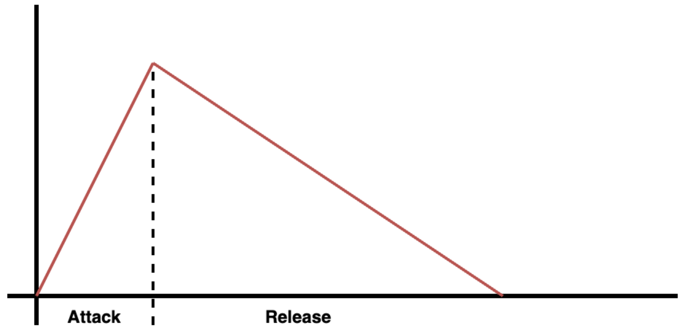
# Modulation

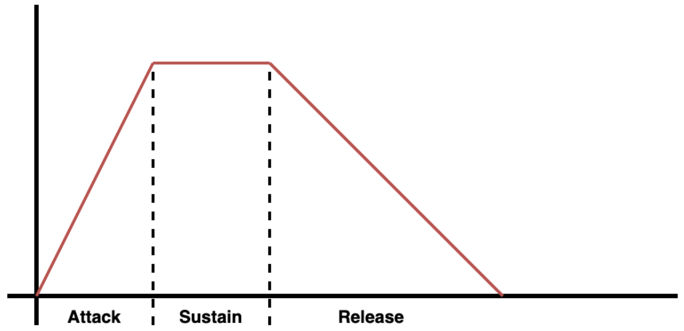
- Sources
  - Waveforms
    - LFO
  - Envelopes
  - Random?
- Targets
  - Anything!
  - Pitch
  - Amplitude
  - Filter cuttoff frequency

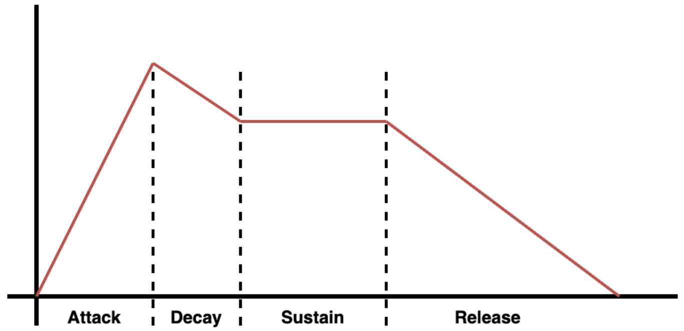


# Envelopes

- Common envelopes
  - AR
  - ASR
  - ADSR







## Haskell

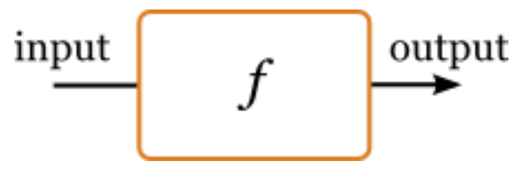
## Euterpea2

- Digital signal processing
  - Generating sound from scratch
- MIDI-based composition

## Euterpea2

- **Render WAV files**
- Live MIDI playback

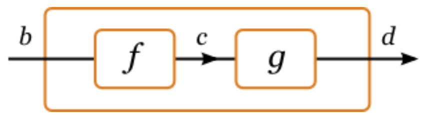
## Arrow Basics

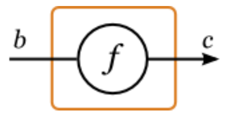


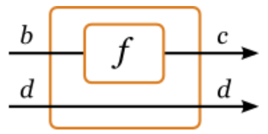
- General abstraction over computation
- Euterpea2 uses arrows to model signal processing
  - We want to generate and/or process audio samples at a suitable rate
  - Nyquist–Shannon
    - 44.1 kHz

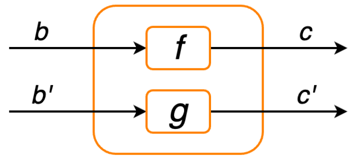
# Arrow Basics

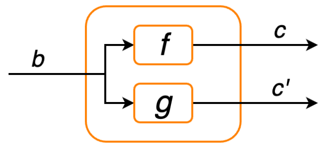
```haskell
class Category cat where
    -- | the identity morphism
    id :: cat a a
    -- | morphism composition
    (.) :: cat b c -> cat a b -> cat a c

class Category a => Arrow a where
    -- | Lift a function to an arrow.
    arr :: (b -> c) -> a b c
    -- | Send the first component of the input through the argument
    --   arrow, and copy the rest unchanged to the output.
    first :: a b c -> a (b,d) (c,d)
    --   The default definition may be overridden with a more efficient
    --   version if desired.
    second :: a b c -> a (d,b) (d,c)
    -- | Split the input between the two argument arrows and combine
    --   their output.  Note that this is in general not a functor.
    (***) :: a b c -> a b' c' -> a (b,b') (c,c')
    -- | Fanout: send the input to both argument arrows and combine
    --   their output.
    (&&&) :: a b c -> a b c' -> a b (c,c')

returnA :: Arrow a => a b b
returnA = id
-- or (arr id), when id :: a -> a
```





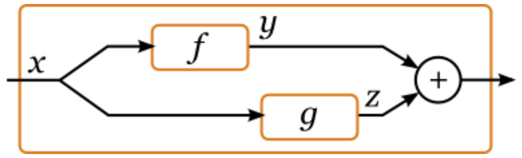


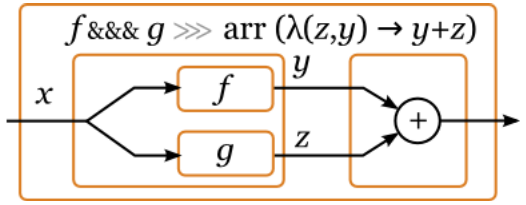




# Arrow Basics

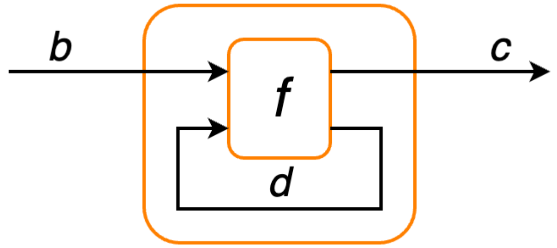
```haskell
-- do-notation / Arrow syntax
addA :: Arrow a => a b Int -> a b Int -> a b Int
addA f g = proc x -> do
                y <- f -< x
                z <- g -< x
                returnA -< y + z

-- Or we could try and be "smart"...
addA f g = f &&& g >>> arr (\(y, z) -> y + z)

-- Constant Arrow
constA :: (Arrow arr) => b -> arr a b
constA = arr . const

-- foldA
foldA :: (Foldable t, Arrow arr) => (b -> c -> c) -> c -> t (arr a b) ->
arr a c
foldA f c = foldr (\sfb sfc -> sfb &&& sfc >>> arr (uncurry f)) (constA c)
```





# Arrow Basics

```haskell
class Arrow a => ArrowLoop a where
    loop :: a (b,d) (c,d) -> a b c

class ArrowLoop a => ArrowCircuit a where
    -- | A delay component
    delay :: b -> a b b

counter :: ArrowCircuit a => a Bool Int
counter = proc reset -> do
            rec output <- returnA -< if reset then 0 else next
                next   <- delay 0 -< output + 1
            returnA -< output
```



# Euterpea2 Types

```haskell
-- An arrow `a b c`, with a phantom type `p`
-- Has Category & Arrow instances if a does
newtype ArrowP a p b c = ArrowP { strip :: a b c }

-- A way of generating `b`s from `a`s.
-- Has Category & Arrow instances
newtype SF a b = SF { runSF :: (a -> (b, SF a b)) }

-- A way of generating `b`s from `a`s,
-- Has Category & Arrow instances, with an extra parameter `clk`
type Signal clk a b = ArrowP SF clk a b
type SigFun clk a b = ArrowP SF clk a b

-- A way of passing the sample rate at the type level
class Clock p where
    rate :: p -> Double

-- No data constuctors!
data AudRate
data CtrRate

instance Clock AudRate where
    rate _ = 44100

instance Clock CtrRate where
    rate _ = 4410

-- A way of generating `b`s from `a`s, at a specific rate
type AudSF a b = SigFun AudRate a b
type CtrSF a b = SigFun CtrRate a b
```

# Wavetable Synthesis

```haskell
data Table = Table
    !Int                        -- size
    !(UArray Int Double)        -- table implementation
    !Bool                       -- Whether the table is normalized

type TableSize = Int
type PartialStrenght = Double

tableLinear :: TableSize -> StartPt -> [(SegLength, EndPt)] -> Table
tableLinearN :: TableSize -> StartPt -> [(SegLength, EndPt)] -> Table
tableSines :: TableSize -> [PartialStrength] -> Table
tableSinesN :: TableSize -> [PartialStrength] -> Table

-- e.g.
-- oscFixed frequency :: AudSF () Double
oscFixed :: forall p a . (Clock p, ArrowCircuit a) => Double -> ArrowP a p () Double
-- osc wavetable phase :: AudSF Double Double
-- But what about the frequency?
osc :: (Clock p, ArrowCircuit a) => Table -> Double -> ArrowP a p Double Double
```

## Envelopes

```
-- [y0, y1, y2, ...]  => (0, y0) (x1, y1) (x2, y2) ...
--    [ x1, x2, ...]

-- IMPORTANT: This function holds the last SLOPE, not the last VALUE
envLineSeg :: Clock p => [Double] -> [Double] -> Signal p () Double

-- IMPORTANT: This function holds the last RATE, not the last VALUE
envExponSeg :: Clock p => [Double] -> [Double] -> Signal p () Double
```

## Effects

```haskell
-- Fixed delay
delayLine :: forall p . Clock p => Double -> Signal p Double Double

-- Dynamic delay, up to a fixed maximum
-- (signal, delay)
delayLine1 :: forall p . Clock p => Double -> Signal p (Double, Double) Double
```

## Filters

```
-- (signal, frequency)
filterLowPass :: forall p . Clock p => Signal p (Double, Double) Double
filterHighPass :: Clock p => Signal p (Double, Double) Double

-- (signal, frequency)
filterLowPassBW :: forall p . Clock p => Signal p (Double, Double) Double
filterHighPassBW :: forall p . Clock p => Signal p (Double, Double) Double
-- (signal, frequency, bandwidth)
filterBandPassBW :: forall p . Clock p => Signal p (Double, Double, Double) Double
filterBandStopBW :: forall p . Clock p => Signal p (Double, Double, Double) Double

-- loop time in seconds
-- (signal, reverb time)
filterComb :: Clock p => Double -> Signal p (Double, Double) Double
```

## White Noise

```haskell
-- seed for the RNG
noiseWhite :: Int -> Signal p () Double
```

# Rendering to WAV

```haskell
-- Double and (Double, Double) are instances of AudioSample
-- e.g., mono or stereo signals
outFile :: forall a p. (AudioSample a, Clock p) =>
    String -- ^ Filename to write to.
    -> Double -- ^ Duration of the wav in seconds.
    -> Signal p () a -- ^ Signal representing the sound.
    -> IO ()
```

## And now?

- Clone the workshop repository
  - https://github.com/mvaldesdeleon/generative-music-with-haskell
- Get your environment up and running
- Try to implement the different challenges
- Play around on your own

## Testing

- Visually inspect the waveform
- Visually inspect the spectrogram
- Listen (carefully!)

## Resources

- Arrows
  - https://www.haskell.org/arrows/syntax.html
  - https://hackage.haskell.org/package/base-4.20.0.1/docs/Control-Arrow.html
  - https://ghc.gitlab.haskell.org/ghc/doc/users_guide/exts/arrows.html
- Euterpea2
  - https://www.euterpea.com/
  - https://hackage.haskell.org/package/Euterpea-2.0.7
  - https://www.euterpea.com/wp-content/uploads/2016/12/euterpea_signal_quick_reference.pdf
  - https://www.euterpea.com/wp-content/uploads/2016/12/Euterpea_Quick_Reference.pdf
- Audacity
  - https://www.audacityteam.org/

# Now go make some noise!

Please don’t fuck up your ears…

## Extras

## Pitches

```haskell
type AbsPitch = Int -- MIDI, 0 to 127, ±1 = ±1 semitone, 60 = C4

data PitchClass = Cff | Cf | C | Dff | Cs | Df | Css | D | Eff | Ds
    | Ef | Fff | Dss | E | Ff | Es | F | Gff | Ess | Fs
    | Gf | Fss | G | Aff | Gs | Af | Gss | A | Bff | As
    | Bf | Ass | B | Bs | Bss
    deriving (Show, Eq, Ord, Read, Enum, Bounded)
type Octave = Int
type Pitch = (PitchClass, Octave)
```

# Notes

```haskell
type Dur = Rational
bn, wn, hn, qn, en, sn, tn, sfn :: Dur

data Primitive a = Note Dur a | Rest Dur
    deriving (Show, Eq, Ord)

data Music a = Prim (Primitive a)
    | Music a :+: Music a -- sequential composition
    | Music a :=: Music a -- parallel composition
    | Modify Control (Music a) -- modifier (e.g., instrument selection)
    deriving (Show, Eq, Ord)

line, chord :: [Music a] -> Music a
line = foldr (:+:) (rest 0)
chord = foldr (:=:) (rest 0)

note :: Dur -> a -> Music a
note d p = Prim (Note d p)

rest :: Dur -> Music a
rest d = Prim (Rest d)
```

# Rendering to SF

```haskell
type Mono p = Signal p () Double
type Stereo p = Signal p () (Double,Double)
type Volume = Int

type Instr a = Dur -> AbsPitch -> Volume -> [Double] -> a
-- Instr (Mono AudRate)
-- Instr (Stereo AudRate)
type InstrMap a = [(InstrumentName, Instr a)]

instrument :: InstrumentName -> Music a -> Music a
tempo :: Dur -> Music a -> Music a -- I *think* 1 = 60 bpm

-- AbsPitch and (AbsPitch, Volume) have ToMusic1 instances
-- Double and (Double, Double) have AudioSample instances
renderSF :: (Clock p, ToMusic1 a, AudioSample b) =>
    Music a ->
    InstrMap (Signal p () b) ->
    (Double, Signal p () b) -- duration and SF we can use to render a WAV
```